# Apple

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**Scientific Name and Introduction:** *Malus* x *domestica* Borkh., the apple, is a perennial of the Rosaceae family. The apple is thought to have arisen in the Caucasus region of southeastern Europe, and the tree is one of the hardiest temperate zone species. The edible part of the fruit is comprised of fleshy tissue that surrounds the five ovaries, as well as some ovary or carpel tissue. The parenchyma of the fused bases of the calyx, corolla, and stamens constitutes the major edible part of the fruit, though this tissue is sometimes interpreted as being cortical. The skin surrounding the fleshy parenchyma tissue is made up of cuticle, epidermal, and hypodermal layers, with lenticels allowing gas diffusion across the skin. Cracks in the skin surface are also important for gaseous exchange. The diffusion characteristics of the skin can impact the tolerance of different varieties to storage conditions. Examples include 'Golden Delicious' which tends to shrivel faster than other varieties because of breaks in the cuticle, and the Marshall McIntosh strain which is less tolerant to low $O_2$ in CA storage than other strains because of higher resistance to gas exchange.

**Quality Characteristics:** Quality consists of a combination of visual appearance, texture and flavor. Modern consumers demand impeccable appearance and optimum texture and firmness typical of the variety.

*Skin color*. Each variety has specific commercial requirements for skin color ranging from green or yellow for varieties such as 'Golden Delicious' and 'Granny Smith' to red for varieties such as 'Red Delicious.' Bi-colored apples such as 'Gala' and 'Braeburn' are also popular. Some varieties are currently marketable only if they meet strict standards for red color intensity and coverage. There is a tendency for wholesalers to gradually increase color standards, thereby encouraging growers to select redder strains of previously acceptable bi-colored apples. Red color is not an indicator of fruit maturity or quality, however. With few exceptions, the ground (background) color requirement for apples is light green, as yellowness is regarded as an indication of overmature or senescent fruit. Recently, consumers have preferred 'Golden Delicious' apples that have a white skin color, rather than green or yellow. Consumers demand fully green 'Granny Smith' apples without a red blush and 100% red color for 'Red Delicious.'

*Blemish*. A high quality apple in the marketplace is free from blemish, although there may be a greater tolerance for defects in certain markets such as organic outlets. However, with the increase in organic production this is changing rapidly. Occurrences of physically induced damage such as bruising or stem-punctures and physiological and pathological disorders are not acceptable in any market. The prevalence of these defects can be affected greatly by variety characteristics such as stem length, skin tenderness, softness of the fruit, and genetically based resistance to physiological and pathological disorders. The density of the flesh and the skin thickness can also contribute to resistance of fruit to bruising under normal handling conditions, and susceptibility to bruising can determine the commercial success of a variety.

*Texture*. A universal constituent of quality regardless of variety is firmness. Consumers demand apples that are crisp and crunchy. Other textural or flavor components are secondary. All apples are not required to have the same firmness values, and optimum values are dependent upon the characteristics of an individual variety. For example, a crisp 'Granny Smith' apple is often 80 to 98 N (18 to 22 lb-force) while a crisp 'Golden Delicious' is above 53 N (12 lb-force).

*Flavor*. Sweetness and acidity vary by variety. For example, the acidity of 'Granny Smith' apples is high (0.8 to 1.2% malate) while that of 'Red Delicious' is low (0.2 to 0.4%). Similarly, sugar content of apples also varies by variety. 'Fuji' apples can have 20% or more SSC.

**Ethylene Production and Sensitivity:** The apple is classified as a climacteric fruit, exhibiting increased respiration rates during maturation and ripening. This rise is associated with increases in internal concentrations of $CO_2$ and ethylene, respiration and autocatalytic ethylene production. Endogenous ethylene production can vary greatly among varieties. In general, early season varieties have high ethylene production rates and ripen quickly, while late season ones have low ethylene production rates and ripen slowly (Watkins, 2001). The timing of the climacteric and ripening of apple fruit is advanced by exposure to ethylene. Prevention or slowing of ethylene production, by affecting ethylene synthesis or perception, is a strategy for increasing fruit storability. This is achieved primarily by use of low storage temperatures and application of CA storage technologies (Watkins, 2002). A new compound, 1-methylcyclopropane (1-MCP), is now available on a limited basis under the commercial name SmartFresh.™ 1-MCP is structurally related to ethylene, has a non-toxic mode of action, is applied at very low levels, with low measurable residues in food commodities.

**Respiration Rates:** In general, early season varieties have high respiration rates, while late season ones have low respiration rates. The respiration rate of fruit is directly affected by temperature, and the respiratory climacteric is suppressed by storage temperatures below 10 °C (50 °F). The lowest temperatures for storage must be above freezing and those at which chilling injury will develop.

| **Temperature** | **Summer apples** | **Fall apples** |
|---|---|---|
| | ($mg\ CO_2\ kg^{-1}\ h^{-1}$) | |
| 0 °C | 3 to 6 | 2 to 4 |
| 5 °C | 5 to 11 | 5 to 7 |
| 10 °C | 14 to 20 | 7 to 10 |
| 15 °C | 18 to 31 | 9 to 20 |
| 20 °C | 20 to 41 | 15 to 25 |

To get mL $kg^{-1}\ h^{-1}$, divide the mg $kg^{-1}\ h^{-1}$ rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg $kg^{-1}\ h^{-1}$ by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data are from Hardenburg et al., 1986.

**Horticultural Maturity Indices:**

*Maturity and Marketing Season*. In general, an apple fruit harvested less mature will have poor color and flavor and can be more susceptible to physiological disorders such as bitter pit and superficial scald. Fruit harvested over-mature tend to be softer, more easily damaged, may have watercore, and be more susceptible to diseases and physiological disorders such as senescent breakdown. The length of storage of apples generally can be increased by harvesting fruit before they are fully mature, but quality characteristics such as varietal flavor decrease as immaturity at harvest increases. Fruit harvested early in the harvest window for long-term storage (6 to 12 mo) tend to have less flavor than those allowed to ripen further on the tree but are acceptable if minimal flavor requirements are met along with good texture. The challenge is to decide appropriate harvest periods for each marketing period, which can range from immediate on-farm sales to marketing across the globe after 11 mo of storage.

*Harvest Maturity Indices*. A wide range of indices has been tested over many years as possible indicators of harvest maturity. Several common methods have been outlined by Lau (1985). Ethylene, measured commonly as internal ethylene concentration, and the starch index, in which the degree of starch hydrolysis is estimated, have become the most widely used maturity indices. Since a rise in ethylene production is associated with initiation of ripening, it has been suggested that ethylene production or internal ethylene concentration (IEC) should be a major determinant of harvest decisions (Lau, 1985). However, relationships between ethylene production and optimum harvest dates can be poor, and the timing, or presence, of increased ethylene production is a function of cultivar, and within a cultivar is greatly affected by factors such as growing region, orchard within a region, cultivar strain, growing season conditions, and nutrition (Watkins, 2002). Therefore, ethylene production may not be relevant for determining harvest of some cultivars.

For some bi-colored apples, background color is considered an important harvest index. In some cases, state regulations have been established to set minimal harvest maturities, eg., in California the starch index for 'Granny Smith.' While ethylene production is regarded as the only *physiological* indicator of apple fruit maturity, fruit of some varieties and growing regions are often harvested well before autocatalytic ethylene production occurs, and therefore this measurement is commercially irrelevant. However, in some regions ethylene is used to determine when fruit are too mature to be candidates for long-term storage. It is generally recognized that no single maturity index is appropriate across all varieties; growers have learned to rely on a combination of indices.

Other indices such as flesh firmness and soluble sugar content are quality indicators rather than maturity indicators, as they are influenced greatly by orchard factors, eg., fruit exposure to light. During the pre-harvest season, firmness falls and sugar content continues to increase. However, these quality indicators provide information that can be important to fruit performance in storage. Both indices are increasingly used in the marketplace as quality criteria by wholesalers, especially in Europe.

The three major apple-growing regions in the U.S., Washington, New York and Michigan, operate apple maturity programs in conjunction with their land grant universities. Currently in Washington State individual packinghouses conduct their own maturity programs inline with their marketing strategies. In each region, a wide range of maturity and quality indices are collected, and the optimum harvest period (harvest window) is established for each variety (Beaudry et al., 1993; Blanpied and Silsby, 1992; *Washington Apple Maturity Handbook*). The strength of these programs lies not in reliance on absolute maturity indices, but on discussion with industry personnel on changes in maturity and quality occurring over the harvest period. In this way, full participation of extension personnel, growers and storage operators can ensure that fruit of appropriate storage potential are directed towards short, medium or long-term storage.

**Grades, Sizes and Packaging:**

*Grade Standards*. U.S. grades are U.S. Extra Fancy, U.S. Fancy, and U.S. No. 1, based primarily on color requirements, but also on freedom from decay, disorders and blemishes, as well as firmness of fruit (Childers et al., 1995). These federal guidelines have been adopted by many states, but states may have additional grading and branding laws. Information pertaining to any state can be obtained from the local state department of agriculture. Washington State packers follow the grade standards of either U.S. Federal regulations or special Washington State Grade Standards promulgated by the Washington State Department of Agriculture (WSDA) in conjunction with USDA.

*Cartons*. Sizing is usually carried out by weight or fruit diameter but is independent of grade. Requirements for fruit size vary greatly by market, but in general larger sizes bring greater returns. Most fruit are packed into bushel cartons, usually 40 lb (18.2 kg), depending on variety, and sold by count (fruit per carton). Apples are most often packed on 4 to 5 soft fiberboard trays made from recycled newspaper. In some cases, the tray may be made of soft polystyrene. Cartons are often unvented. However, unvented cartons on pallet stacks will cool slowly, detrimentally affecting product longevity. Venting to improve cooling rates of fruit is becoming more common.

A two-layer carton that is wider, known as the 60 x 40 pack, is becoming more common in the U.S. and for export to Europe. It has the advantage of minimizing fruit handling as the cartons are placed directly onto display racks at retail.

Most apples are sold loose, although fruit are increasingly available in polyethylene bags of 3, 5, or 10 lb (1.4, 2.3, or 4.5 kg). These bags were originally used for marketing smaller fruit, but are now used for all qualities and sizes. Bags are most often sold in warehouse-type retail stores. Consumer packages in which 2 to 6 apples, or a combination of fruits, are shrink-wrapped are becoming more popular in some retail outlets. Shrink-wrapped packages reduce the time consumers spend in the produce section, and also reduce loss caused by consumer sorting and handling of individual fruit.

**Cooling Conditions:** The rate of cooling of apple fruit affects retention of quality, but its importance varies according to variety, harvest maturity, nutritional status of the fruit and storage history. It is very important to rapidly cool apple varieties that mature in the early part of the harvest season (Summer varieties) since they will soften more rapidly than those that mature in the later part of the harvest season. Within a variety, apples tend to soften more rapidly at later stages of maturity than earlier stages. Effects of slow cooling are magnified as storage length increases. Therefore, inadequate investment of resources at harvest to ensure rapid fruit cooling may not be apparent until late in the storage period when fruit may not meet minimum firmness standards for marketing. For example, a 1-day delay at 21 °C (69.8 °C) before cooling results in a 7 to 10 day loss of storage-life for 'McIntosh.' The effects of delays before cooling of fruit, irrespective of timing of CA conditions, are illustrated for 'Empire' apples in Table 1.

Table 1. Effect of cooling rate on firmness of rapid CA Empire apples. Modified from Blanpied (1986).

| Days to cool to 0 °C | Days from harvest to 3% $O_2$ | Flesh firmness (N) at removal from CA |
|---|---|---|
| 1 | 4 | 63 |
| 7 | 4 | 58 |
| 14 | 4 | 52 |

Apple fruit can be cooled by room cooling, forced-air cooling, or hydro-cooling. Forced-air cooling and hydro-cooling systems can be used to rapidly reduce fruit temperatures, but they are not widely used for apples in the U.S. Room-cooling, in which normal air flow within the storage room cools the fruit, is the predominant method in most regions. However, air flows around rather than through bins of fruit, and therefore this method is slow and inefficient. Rapid cooling is often difficult to accomplish when rooms are filled rapidly and refrigeration capacity was not designed for a large fruit load. This problem can be overcome in two ways. First, fruit can be separated and loaded into a number of rooms for pre-cooling before being moved into long-term storage. A second option is to load only the quantity that can be handled by the existing refrigeration system.

When refrigeration capacity is a limiting factor, no more than two stacks of bins should be placed across the width of the storage room each day, and that should be reduced to one stack if the air temperature in the room is not down to 0 °C (32 °F) by the next morning (Bartsch and Blanpied, 1990). Faster cooling will be obtained if bins are placed in the downstream discharge of the evaporator with pallet runners oriented in the same direction as the air flow. Additional bins of fruit should be stacked, no more than two high, in unfilled refrigeration rooms to cool overnight before loading into the CA room the next morning. These stacks should be placed randomly throughout the unfilled room to maximize air exchange with the fruit. Capacity to cool fruit is dependent on refrigeration capacity and room design. A qualified refrigeration engineer should assist in the development of a cooling program.

Maximizing quality maintenance of fruit requires attention not only to temperature immediately after harvest, and during storage, but also during packing, transport, and retail display. This combination of events is sometimes described as the "cold chain," highlighting the importance of maintaining the links from harvest to consumer.

Excellent discussions of cooling can be found in Postharvest Technology of Horticultural Crops (Univ. of California, Pub. No. 3311), Commercial Cooling of Fruits, Vegetables and Flowers (Univ. of California, Pub. No. 21567), and Bartsch and Blanpied (1990).

**Optimum Storage Conditions:** Apple producers have learned that apple fruit respond dramatically to both temperature and atmosphere modification. Rapid temperature reduction and the exacting maintenance of low temperatures close to the chilling point of the variety can provide good to medium quality product following 3 to 6 mo of storage and in some cases longer. However, modern commercial warehouses couple temperature management with CA for long-term storage of apples.

*Regular air storage*. The recommended conditions for commercial storage of apples are -1 °C to 4 °C (30.2 to 39.2 °F) and 90 to 95% RH, depending upon variety. Typical storage periods for a number of varieties in air are shown in Table 2. The duration of air storage has become shorter over the last several years as quality standards in the market have increased. Also, short-term CA storage is becoming more common as the period available for sale of air-stored fruit has decreased.

Table 2. Storage characteristics of several apple varieties. Modified from Watkins and Blanpied (2001).

| | **Potential months of storage** | | | |
|---|---|---|---|---|
| **Variety** | **0 ºC air** | **CA*** | **Superficial scald susceptibility** | **Comments** |
| Braeburn | 3-4 | 8-10 | Slight | Sensitive to $CO_2$. |
| Cortland | 2-3 | 4-6 | Very high | Temperature sensitive; McIntosh conditions preferred; Scald inhibitor essential. |
| Delicious | 3 | 12 | Moderate to very high | Sensitive to $CO_2 > 2\%$; Scald inhibitor essential. |
| Empire | 2-3 | 5-10 | Slight | Avoid late harvest; Temperature sensitive; Scald inhibitor not required. $CO_2$ sensitive. |
| Fuji | 4 | 12 | Slight | Late harvested fruit may be $CO_2$ sensitive. |
| Gala | 2-3 | 5-6 | Slight | Loses flavor during storage. |
| Golden Delicious | 3-4 | 8-10 | Slight | Susceptible to skin shrivel. |
| Granny Smith | 3-4 | 10-11 | Very high | Sensitive to $CO_2$. |
| Idared | 3-4 | 7-9 | Slight | Temperature sensitive; Tolerant to orchard freezing damage. |
| Jonagold | 2 | 5-7 | Moderate | Avoid late harvest; May develop scald. |
| Jonamac | 2 | 3 | Moderate | Loses flavor during storage. |
| Law Rome | 3-4 | 7-9 | Very high | Scald inhibitor essential. |
| Macoun | 3 | 5-7 | Slight | Can be stored with McIntosh. |
| McIntosh | 2-3 | 5-7 | Moderate | $CO_2$ sensitive; Normal storage is sometimes shortened by excessive flesh softening; Scald inhibitor recommended in regions other than the Champlain. |
| Mutsu | 3-4 | 6-8 | Slight | Green apples have low eating quality. |
| Spartan | 3-4 | 6-8 | Slight | Can be susceptible to high $CO_2$. Susceptible to skin shrivel at 36 to 38 °F. |

| | | | | |
|---|---|---|---|---|
| Stayman | 2-3 | 5-7 | High | Will tolerate $CO_2$ up to 5% but usually stored in 2 to 3% $CO_2$. Scald inhibitor essential. Susceptible to skin shrivel. |

* The potential months storage are for rapid CA and range from those obtained with standard CA to those obtained with low $O_2$ and low ethylene CA. Growing region affects storage periods obtained even under optimal CA conditions.

Temperatures for air-stored fruit are affected by sensitivity of the variety to low temperature disorders. While lower temperatures usually result in firmer and greener fruit, some varieties such as 'McIntosh' can develop core browning, soft scald and internal browning when held at temperatures below 3 °C (37.4 °F). However, these disorders typically develop only in fruit kept for more than several months, so risks of low-temperature injury are low for fruit kept in short-term storage (2 to 3 mo). An additional factor to consider in selecting storage temperatures, is the impact of temperature on RH requirements. It is easier to maintain RH > 90% at 1 °C (33.8 °F) than 0 °C (32 °F). Final decisions should be based on experience with a variety and advice of extension personnel.

Most apple varieties are not sensitive to chilling temperatures and should be stored as close to 0 °C (32 °F) as possible. However, varieties that are susceptible to low temperature disorders should be stored at 2 to 3 °C (35.6 to 337.4 °F). Temperatures also should be increased for fruit stored in low $O_2$ CA, since lower temperatures increase risk of low $O_2$ injury.

Temperature in storage rooms should be monitored throughout the storage period using thermocouples throughout the room (Bartsch and Blanpied, 1990). It is dangerous to rely on a single thermometer at the door, as temperatures within stacks and throughout the room may be lower or higher than indicated by such readings. Faster fruit ripening and greater refrigeration usage result when fruit temperatures are too high (Table 3). Excessive temperatures after packing due to lack of cooling or developing during transport to market can negatively impact quality at the consumer level. Fruit temperatures can increase during packing; failure to remove heat may result in subsequent loss of firmness during transport (Kupferman, 1994; Watkins, 1999).

Table 3. Rates of heat evolution (BTU per ton per day) by ten apple varieties at different temperatures. [1]Adapted from Tolle (1962). To convert BTU $ton^{-1}$ $day^{-1}$ to kJ per ton per day,multiply by 1.055.

| | Temperature | | | | |
|---|---|---|---|---|---|
| | -1 °C | 0 °C | 2.2 °C | 3.3 °C | 4.4 °C |
| Cultivar | | | | | |
| Delicious | 690 | 760 | 910 | 1,010 | 1,110 |
| Golden Delicious | 730 | 800 | 970 | 1,070 | 1,180 |
| Jonathan | 800 | 880 | 1,060 | 1,170 | 1,290 |
| McIntosh | 730 | 800 | 970 | 1,070 | 1,180 |
| Northern Spy | 820 | 900 | 1,090 | 1,200 | 1,320 |
| Rome Beauty | 530 | 580 | 700 | 780 | 850 |
| Stayman Winesap | 820 | 910 | 1,100 | 1,210 | 1,330 |
| Winesap | 530 | 590 | 710 | 780 | 860 |
| Yellow Newton | 510 | 570 | 690 | 760 | 840 |
| York Imperial | 610 | 670 | 810 | 900 | 990 |
| Mean | 680 | 750 | 900 | 1,000 | 1,100 |

**Controlled Atmosphere (CA) Considerations:** Apples are the predominant horticultural commodity stored under CA conditions, but the gas composition and storage temperature conditions are specific to variety, growing region, and sophistication of the equipment available for monitoring and controlling the atmospheres. Interactions occur between $O_2$, $CO_2$ and temperature. For example, low storage temperatures increase fruit susceptibility to low $O_2$ injury. Also when very low $O_2$ levels are utilized, levels of $CO_2$ should be reduced to prevent $CO_2$ damage.

The wide range of recommended atmospheres has been reported by Kupferman (1997) and reflects the above factors as well as strategies employed by different industries. Information about CA recommendations for varieties in any growing region should be obtained from local extension personnel.

Until the mid 1970's, 8 to 10 days were often required to load a CA room and a further 15 to 20 days were needed for fruit respiration to lower $O_2$ to 2.5 to 3%. Fruit quality resulting from these conditions gradually became unacceptable in the marketplace. Rapid CA is now standard practice in many apple industries. Nitrogen flushing equipment enables $O_2$ in CA rooms to be reduced to less than 5% within a few days (h) of harvest, although 4 to 7 days from the time of harvest of the first fruit moved into the room to CA conditions is considered "rapid CA." For certain varieties, fruit core temperatures must be reduced to predetermined thresholds *before* application of CA. Even when rooms are filled over extended periods, $O_2$ concentrations are usually lowered by flushing with $N_2$, and it is becoming more common to use $N_2$ flushing for re-sealing rooms that are opened briefly to remove some of the fruit required for marketing. Nitrogen used for flushing is either purchased in tanks or generated on site.

An RH of 90 to 95% is recommended for apples to prevent shrivel. The major causes of dehydration are small coil surface areas and/or frequent defrosting. When CA rooms are designed, the refrigeration engineer should demand the largest coil size feasible for the room. Operators have been reducing the number of defrost cycles to an absolute minimum to optimize RH in the room. Some operators reduce the $O_2$ to the minimum safe level and then raise the temperature to 1 to 2 °C (33.8 to 35.6 °F) to minimize the need to defrost. Some storage rooms are outfitted with high pressure water vapor systems that add moisture to the room and are suited for operation at around 0 °C (32 °F). The air distribution system should be designed to prevent condensation of water droplets on fruit to prevent decay. The use of plastic rather than wooden bins, or poly tubes (bin liners) inside wooden bins, has also helped minimize shrivel of 'Golden Delicious.'

Once fruit have been cooled and CA conditions established, CA storage regimes fall into one of three categories, depending on level of equipment and technology involved.

*Standard CA* involves conservative atmosphere conditions used with minimum risk of gas-related injuries (Table 4). Control of these atmospheres may be manual by daily reading and adjustment, or via computer controlled equipment. The margin of safety is large enough so that fluctuations in gas concentrations in manually adjusted storages should not cause fruit injury.

*Low $O_2$ CA storage* requires that fruit be kept at $O_2 < 2\%$, but above the concentration at which fermentation will occur. Non-descriptive terms such as 'ultralow' are sometimes used but should be avoided in favor of describing specific $O_2$ percentages. The safe $O_2$ concentration varies by cultivar (Table 4) and region. Delicious apples from British Columbia, Canada, for example, can be stored safely at 0.7% (Lau, 1997) allowing control of superficial scald without use of diphenylamine (DPA). Fruit of the same cultivar from other growing regions may show injury when stored at these low $O_2$ levels (Lau et al., 1998). Strains within a variety can also vary in sensitivity (Lau, 1997). An extreme case is the Marshall strain of 'McIntosh' where $O_2 < 4$ to 4.5% are not safe whereas 2 to 3% $O_2$ is acceptable for other 'McIntosh' strains (Park et al., 1993). In general, it is necessary to increase storage temperature when low $O_2$ CA storage is used. A number of guidelines have been developed for safe operation of long-term CA storage. Using these techniques, it has also been possible to minimize risk of low $O_2$ injury *in the northeastern U.S:*

Apply low $O_2$ CA storage only to apples harvested early in their harvest window. Over-mature fruit can be damaged by low $O_2$ storage.

Avoid apples from orchard blocks that average fewer than five seeds per apple. Low seed count can be a problem with some varieties.
Reduce core temperatures to 1 to 2 °C within 2 days after harvest for ‘McIntosh’ and ‘Empire.’ (In Washington, cooling can take longer as it is done under CA, with the exceptions of ‘Fuji’ and ‘Braeburn’).
Decrease $O_2$ < 5% within 7 days after harvest, except for ‘Fuji’ and ‘Braeburn.’
Raising storage temperatures from 0 to 2 °C can reduce risk.
Automatic gas analysis/control equipment to eliminate $O_2$ fluctuations that may lead to low $O_2$ injury.
Avoid use of postharvest drench with DPA where possible; it’s application has been associated with low $O_2$ injury, eg., for varieties with low scald risk.

Table 4. Atmospheric and temperature requirements for standard CA storage of apples.

| **Variety** | **$CO_2$ (%)** | **$O_2$ (%)** | **Temperature °C** | **Low $O_2$ (1.5 to 1.8%) storage potential (Eastern U.S.)** |
|---|---|---|---|---|
| Braeburn | 0.5 | 1.5-2 | 1 | yes |
| Cortland | 2-3 | 2-3 | 0 | no |
| | 2-3 (for 1 mo) then 5 | 2-3 | 2 | |
| Delicious | 2 | 0.7-2 | 0 | yes |
| Empire | 2-3* | 2 | 2 | yes |
| Fuji | 0.5 * | 1.5-2 | 0-1 | yes |
| Gala | 2-3 | 1-2 | 0-1 | yes |
| Golden Delicious | 2-3 | 1-2 | 0-1 | yes |
| Granny Smith | 0.5 | 1.5-2 | 1 | yes |
| Idared | 2-3 | 2 | 1 | yes |
| Jonagold | 2-3 | 2-3 | 0 | yes |
| Jonamac | 2-3 | 2-3 | 0 | no |
| | 2-3 (for 1 mo) then 5 | 2-3 | 2 | |
| Law Rome | 2-3 | 2 | 0 | yes |
| Macoun | 5 | 2-3 | 2 | no |
| McIntosh | 2-3 (for 1 mo) then 5 | 3 | 2 | no |
| | 2-3 (for 1 mo) then 5 | 2 | 3 | |
| Marshall McIntosh | 2-3 (for 1 mo) then 5 | 4-4.5 | 2 | no |
| Mutsu | 2-3 | 2 | 0 | yes |
| Spartan | 2-3 | 2-3 | 0 | yes |

| | | | | |
|---|---|---|---|---|
| **Stayman** | 2-5 | 2-3 | 0 | yes |

* $CO_2$ sensitive, keep $CO_2$ well below the $O_2$ level. If not treated with DPA, use 1.5 to 2% $CO_2$ during the first 30 days.

*Low ethylene CA storage*. Apple fruit are climacteric, with autocatalytic ethylene production often beginning close to harvest. However, rates of ethylene production can vary greatly among apple varieties. An important physiological effect of CA storage is inhibition of either ethylene production or its action due to lowered $O_2$ or increased $CO_2$.

Low ethylene CA storage has been evaluated as a method for reducing superficial scald, as a safe substitute for low $O_2$ CA storage, and for retarding flesh softening and other forms of senescence (Blanpied, 1990). Low ethylene CA storage (< 1 ppm or 1 $\mu L\ L^{-1}$) was used successfully in New York for storage of the naturally low ethylene-producing 'Empire' apple, but it has been replaced by low $O_2$ storage. In general, low ethylene CA storage has not proven successful for maintenance of fruit quality if levels of ethylene gas within the fruit cannot be controlled, and generally the return on investment in this technology has been poor.

Other methods used in conjunction with CA storage to maintain quality of apple fruit include treatments using short-term stress levels of low $O_2$ or high $CO_2$. In varieties including 'Granny Smith,' 'Delicious,' and 'Law Rome,' $O_2$ of 0.25 to 0.5% for up to 2 weeks has resulted in control of superficial scald (Little et al., 1982; Wang and Dilley, 2000). High $CO_2$ (15 to 20%) treatments before application of CA storage were used for maintenance of firmness of 'Golden Delicious' apples in northwestern North America, but generally are no longer recommended due to fruit damage (Blanpied, 1990).

Under commercial conditions, fruit from CA rooms should be sampled at monthly intervals to detect development of any storage problems and therefore reduce the chances of major fruit losses. Sampling should be carried out by placing representative samples of fruit near a sampling port in the door of the CA room. Samples should be kept in mesh bags rather than plastic bags to prevent false positive readings for scald.

**CA and Apple Varieties:** The selection of CA atmospheres and temperature must take into consideration the variety and in some cases, as mentioned above, the strain of a particular variety, in addition to where it was grown. Experience in Washington has shown that varieties can be divided into two types: those tolerant of high $CO_2$ and those that are not.

*'Gala' and 'Golden Delicious' are $CO_2$-tolerant* varieties which also benefit from rapid reduction of atmosphere. In Washington, fruit with moderate pulp temperatures can be placed into a low $O_2$ environment without danger of $CO_2$ damage. Rapid CA is valuable because it helps retain fruit firmness and acidity better than slowly established CA on these varieties. Washington grown 'Gala' and 'Golden Delicious' can be stored as low as 1.0% $O_2$ with $CO_2$ levels up to 2.5% at 1 °C (33.8 °F). If the temperature is lowered below this point, $O_2$ is raised. Regular storage is 0 °C (32 °F).

*'Fuji,' 'Braeburn' and 'Granny Smith' are varieties in the $CO_2$-intolerant* category. Their cells are densely packed and air exchange within the fruit is therefore reduced. In Washington, these apples must have the flesh temperature close to the storage temperature *before* the $O_2$ is reduced. These varieties have a tendency to develop internal browning, a $CO_2$ damage symptom that is associated with a natural predisposition of the variety (and pre-harvest factors as well as storage regime). $CO_2$ should remain well below the $O_2$ level at all times, and temperatures should be slightly elevated. For example, fruit stored at 1.5% $O_2$ are stored with $CO_2$ below 0.5% at 1 °C (33.8 °F) if fruit are appropriately mature at harvest. It is not advisable to store waxed fruit in boxes with polyliners in CA, as this can hinder air exchange within fruit.

*'Red Delicious'* is somewhat $CO_2$-tolerant and is also tolerant of rapid CA. However, producers have not seen the dramatic positive effects of rapid CA on 'Red Delicious' that have been noted on 'Golden Delicious' or 'Gala.' Delicious fruit soften more rapidly in a bin than on the tree, so CA should not be delayed after harvest. Typical regimes for CA of non-watercored 'Red Delicious' are 1.5% $O_2$ and up to 2.0% $CO_2$ at 0 to 1 °C (32 to 33.8 °F).

*State regulations on CA storage cover both the safe operation and use of the legal definition of "Controlled atmosphere" for stored apples. Regulations include the rate of establishment of CA conditions, the maximum level of* $O_2$ *permitted and the length of time fruit are in CA. Since regulations vary from state to state, operators need to contact their state Department of Agriculture.*

*Many precautions must be taken to assure the safe operation of CA storage rooms. Operators must be aware of the risks of working with* $O_2$ *levels below those needed for survival. Death can be almost instantaneous. Additional precautions must be taken when working with CA generators to avoid implosion or explosion hazards. In short, workers must be thoroughly trained. Contact your local extension office for information about safety in CA.*

**1-Methylcyclopropene (1-MCP):** Softening, yellowing, respiration, loss of titratable acidity, and sometimes a reduction in SSC, as well as development of several physiological disorders, are delayed or inhibited by 1-MCP application (Watkins, 2001). Responses of fruit to 1-MCP may be affected by cultivar and fruit maturity. Volatile production by apples also is inhibited by 1-MCP, being consistent with the view that volatile production is regulated by ethylene. Consumer studies on acceptability of 1-MCP treated fruit will be required to ensure flavor is not unacceptably compromised.

**Retail Outlet Display Considerations:** Keeping apple fruit cold reduces metabolic rates and maintains fruit quality, but the trend in most new retail outlets is not to have refrigeration in display tables. Moreover, typical displays in U.S. supermarkets employ stacking of loose fruit with increased risk of bruising. There is some movement towards use of display cartons such as the 60 x 40 box, which reduces the need to handle fruit and ensures more rapid turnover of product.

**Physiological Disorders:** A wide variety of physiological disorders are found in apple fruit, but susceptibility varies by variety, pre-harvest factors and postharvest conditions (Lidster et al., 1990; Smock, 1977). Disorders can be considered in three categories:

*Disorders that develop only on the tree.* The most important of these is watercore in which intercellular air spaces in the core and cortical tissues become filled with liquid, predominantly sorbitol (Marlow and Loescher, 1984). Usually the occurrence of watercore is associated with advancing fruit maturity and low night temperatures prior to harvest, but a variant of the disorder can occur as a result of heat stress. Presence of watercore in fruit at harvest creates problems in certain varieties such as Delicious because fruit with moderate or severe watercore can develop breakdown during storage. By comparison, grade standards for 'Fuji' have recently been modified so that watercore in 'Fuji' apples is not a grade defect in the U.S. or Canada because watercore is a desirable feature for this cultivar due to the sweetness it imparts to the fruit. Mild or moderate watercore should not be a problem in storage of 'Fuji' if fruit are cooled prior to reduction of $O_2$. Severely watercored fruit should not be placed in CA since breakdown will develop over time.

*Disorders that develop on the tree and during storage*. Bitter pit is a disorder characterized by development of discrete pitting of the cortical flesh, the pits being brown and becoming desiccated with time (Ferguson and Watkins, 1989). The pits may occur predominantly near the surface or deep in the cortical tissue. An associated disorder, known as lenticel blotch, is also observed in some varieties. The incidence and severity of bitter pit are affected by variety, but within a variety bitter pit is related to harvest date and climate; in susceptible varieties, harvest of less mature fruit can result in higher bitter pit incidence, as can excessive pruning or high temperatures and/or droughty conditions during the growing season. Effects of climatic conditions are at least partly related to low calcium concentrations in the fruit. Development of bitter pit during storage results in financial loss and a number of strategies have been employed to prevent its occurrence (Ferguson and Watkins, 1989). These include prediction of risk based on mineral (mainly low calcium) content at harvest or infusion of magnesium. Rapid cooling, CA storage, and application of postharvest calcium drenches may be able to reduce its occurrence. Recommended rates for application of calcium vary by variety and region; product labels should be followed in conjunction with advice of the local extension specialist. Preharvest applications of calcium may be far more effective than postharvest drenching as a means for increasing the concentration of fruit calcium and reducing bitter pit.

*Disorders that develop during storage*. These can be divided into senescent breakdown disorders, chilling disorders and disorders associated with inappropriate atmospheres during storage. Senescent breakdown incidence is related to harvest of overmature fruit and/or fruit with low calcium content. It can be exacerbated by storing fruit at higher than optimal temperatures. Fruit of susceptible varieties are commonly drenched with calcium before storage, but incidence of senescent breakdown can also be reduced by harvesting fruit at a less mature stage, rapid cooling and reducing storage duration. The most common disorders associated with temperature and atmospheres are superficial scald, soft scald, low temperature breakdown, brown core, internal browning, low $O_2$ injury, and high $CO_2$ injury.

**Specific Disorders:**

*Superficial scald* (syn. storage scald) is a physiological disorder associated with long-term storage (Ingle and D'Souza, 1989). It was the major cause of apple fruit loss until the advent of postharvest DPA treatments. Variety, climate, and harvest date affect susceptibility of fruit to the disorder, and decisions about treatment with DPA should be made after consultation with a local extension specialist. DPA is usually applied with a fungicide to reduce decay incidence, and calcium salts may also be included at the same time to reduce bitter pit or senescent breakdown. Application of label rates of clean DPA should prevent DPA-induced fruit damage and exceeding residue tolerances. The risk of DPA damage to fruit increases if DPA is not discarded when soil accumulates in the solution. Both DPA use and DPA residues on imported fruit are prohibited in some countries. Another antioxidant, ethoxyquin, is no longer permitted for use on apples. Low levels of $O_2$ in CA storage reduce the risk of scald developing and also may permit use of lower DPA concentrations. Alternative ways of controlling superficial scald are being investigated, and storage operators are reducing use of DPA where possible. Low $O_2$ and low ethylene CA storage also reduce scald incidence. In British Columbia, Canada, 0.7% $O_2$ storage is used as a substitute for DPA treatment (Lau, 1997). This technique cannot be used universally because fruit grown in other regions may be susceptible to low $O_2$ injury or the risk of scald may be greater due to climate or variety.

*Soft scald* is characterized by irregular but sharply defined areas of soft, light brown tissue that may extend into the cortex. Susceptibility of fruit to soft scald is variety- and climate-related, but effects of harvest maturity are inconclusive. Over-maturity is almost always a contributing factor in 'Golden Delicious.' Storing fruit at 3 °C rather than at lower temperatures can sometimes control the disorder, and DPA used for control of superficial scald may also reduce incidence of soft scald. Storage at a lower temperature following prompt cooling can reduce the incidence of soft scald on 'Golden Delicious.'

*Chilling-related disorders*. Low temperature breakdown, brown core and internal browning are affected by variety sensitivity to low temperatures and generally increase in incidence and severity as the length of storage is increased. Climate affects sensitivity of fruit to the disorders, with more problems occurring after colder, wetter growing seasons. Low temperature breakdown is characterized by markedly brown vascular bundles, browning of flesh, and a clear halo of unaffected tissue underneath the skin. In contrast to senescent breakdown, the affected tissues are more likely to be firmer, more moist, and darker in color. Brown core (syn. coreflush) involves browning of the flesh, initially in the core area and later in the cortex, where it becomes difficult to distinguish from low temperature breakdown. Internal browning does not involve breakdown of the flesh, but rather a graying of flesh apparent when apples are cut. Internal browning and coreflush are often associated with higher $CO_2$, since both can occur in CA when $CO_2$ is higher than $O_2$.

*Low $O_2$ injury* affects fruit in a number of ways. The first indication of injury is loss of flavor, followed by fermentation-related odors. These odors may disappear if storage problems are identified soon enough and severe injury has not occurred. Injury symptoms range from purpling or browning of the skin in a red colored variety, to development of brown soft patches resembling soft scald, to abnormal softening and splitting of fruit. As discussed earlier, varieties vary greatly in response to low $O_2$, and susceptibility to injury is influenced by a number of pre-harvest and postharvest factors.

*$CO_2$ injury* may be external or internal. The external form consists of wrinkled, depressed colorless or colored areas restricted to the skin surface and usually on the greener side of the fruit. Internal forms are expressed as brown heart and/or cavities in the flesh. Recent studies have shown that DPA can reduce incidence of both external and internal $CO_2$ injuries.

**Postharvest Pathology:** The main postharvest diseases of apples that develop in storage are blue mold caused by *Penicillium* species and gray mold caused by *Botrytis cinerea*. Blue mold is the most common and destructive of all the rots. Most blue mold decays are caused by *P. expansum*, but *P. solitum, P. commune,* and *P. crustosum* are also common postharvest pathogens of apples (Sanderson and Spotts, 1995). *Penicillium* species enter fruit primarily through cuts, stem punctures, and bruises (Wright and Smith, 1954). However, some cultivars of apples can also be invaded via the stem during long-term CA storage (Rosenberger, 1999).

Numerous other pathogens can also appear in stored apples (Jones and Aldwinckle, 1990; Pierson et al., 1971; Snowdon, 1990). Some postharvest pathogens infect fruit in the field but remain latent or quiescent until after apples are harvested and placed into storage. These include the *Colletotrichum* species that cause bitter rot, *Botryosphaeria* species that cause black rot and white rot, and *Pezicula malicortis*, the cause of bull's eye rot (Rosenberger, 1990). Postharvest decays initiated in the field must be controlled using fungicides or other disease management strategies during the growing season.

Blue mold and gray mold have been controlled since the early 1970's using postharvest applications of benzimidazole fungicides. Thiabendazole (TBZ), benomyl, and thiophanate-methyl were all registered for postharvest use on apples until the postharvest labels for benomyl and thiophanate-methyl were withdrawn in the early 1990's. TBZ is usually applied immediately after harvest in combination with the antioxidant DPA (Hardenburg and Spalding, 1972). TBZ may be applied a second time as a line spray or in wax as apples are packed.

Benzimidazole-resistant strains of *P. expansum* and *B. cinerea* were discovered in apple storages during the mid- to late-1970's. However, postharvest application of a benzimidazole plus DPA continued to control blue mold and gray mold because most benzimidazole-resistant strains of the pathogen were highly sensitive to DPA (Rosenberger and Meyer, 1985; Sharom and Edgington, 1985). During the mid-1990s, the incidence of blue mold began to increase in some apple packinghouses where the predominant strains of *P. expansum* had developed resistance to benzimidazole-DPA combination. Gray mold is still controlled by the benzimidazole-DPA combination, presumably because it does not recycle on field bins as readily as does *P. expansum*, and it therefore has been subjected to less selection pressure for fungicide resistance.

Captan has a postharvest registration but has proven only moderately effective for controlling *P. expansum* and *B. cinerea.* Captan residues are not acceptable in some export markets. The new fungicide fludioxonil is very effective for controlling *P. expansum* on apples (Rosenberger et al., 2000). Fludioxonil is not yet approved for use on apples in the U.S., but it may receive an EPA registration in the near future.

Much effort has been devoted to development of biocontrols for postharvest diseases of apples (Chand-Goyal and Spotts, 1997; Wisniewski et al., 1995; Roberts, 1990; Janisiewicz, 1998; Mercier and Wilson, 1994; Filonow et al., 1996). The controlled postharvest environment theoretically should allow selection of biocontrol agents particularly suited to those environments. Many of the biocontrol agents selected and developed to date have proven very effective in controlled tests, but commercialization of biocontrols has been slow. Product developers view the market potential for postharvest treatments as relatively limited because the products are applied in a closed environment rather than being sprayed over thousands of acres as are conventional fungicides used to protect crops in the field. Furthermore, liabilities involved in postharvest treatment of apples are considerable both because of the value of the stored crop and because apples as a commodity have previously been spotlighted in debates relating to food safety issues. In addition, devising shelf-stable formulations of biocontrol agents has been difficult. Some currently registered products must be kept frozen until use. Activity of biocontrol organisms may be compromised by excessively high pathogen inoculum or by presence of other compounds in postharvest treatment mixtures.

Biocontrols generally cannot provide eradicant activity against established infections. Thus, infections by *P. expansum* that occur during harvest can be controlled with TBZ fungicide that is applied several hours later whereas most biocontrol agents are ineffective if the pathogen is already established in the infection court when the biocontrol is applied. Using combinations of biocontrols and reduced rates of TBZ may be more effective than using either product alone (Chand-Goyal and Spotts, 1997). When such combinations are used, the chemical fungicide may provide eradicant and short-term protectant activity necessary to prevent decays until the biocontrol agents become established in wounds or other infection courts. Biocontrols provide some protection against TBZ-resistant strains of the pathogens for which no other controls are currently available.

Regardless of the postharvest fungicide or biocontrol strategies that may evolve from current research, good sanitation will remain essential for reducing disease incidence. Inoculum for blue mold recycles from year to year on contaminated field bins and in packinghouses and cold storage rooms (Rosenberger, 2001). Recycling of *P. expansum* on field bins results in repeated exposure of the same pathogen strains to postharvest fungicide treatments, thereby contributing to more rapid selection of fungicide-resistant strains. Badly contaminated bins should be cleaned and disinfested (steam-cleaned) before they are re-used for a new crop. Plastic bins may carry less inoculum than wooden bins. Plastic bins also have the advantage of reducing bruising and abrasion where apples contact the sides of bins. Careful fruit handling, rapid cooling after harvest, and storage at recommended temperatures also help limit postharvest decays.

**Quarantine Issues:** These vary widely according to marketplace and country and guidance should be sought from the local Department of Agriculture.

**Suitability as Fresh-cut Product:** As for other fruit, methods to reduce senescence and browning processes in cut apples are being investigated and commercial products are available (Lee and Smith, 1995). However, potential for improvement is large.

**Additional Information and Websites:** Many states have workshops and materials available. Washington, Michigan and New York offer regular CA workshops and proceedings are available from Michigan State University and Cornell University, respectively. Contact your local extension office or horticulture society to obtain information for your state. In addition, newsletters are available. Examples of information sources are the Cornell Fruit Handling and Storage Newsletter (www.hort.cornell.edu) and the Washington State University website at www.postharvest.tfrec.wsu.edu.

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